Modeling Martian Surface Thermal Environments in Thermal Desktop

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Presented By

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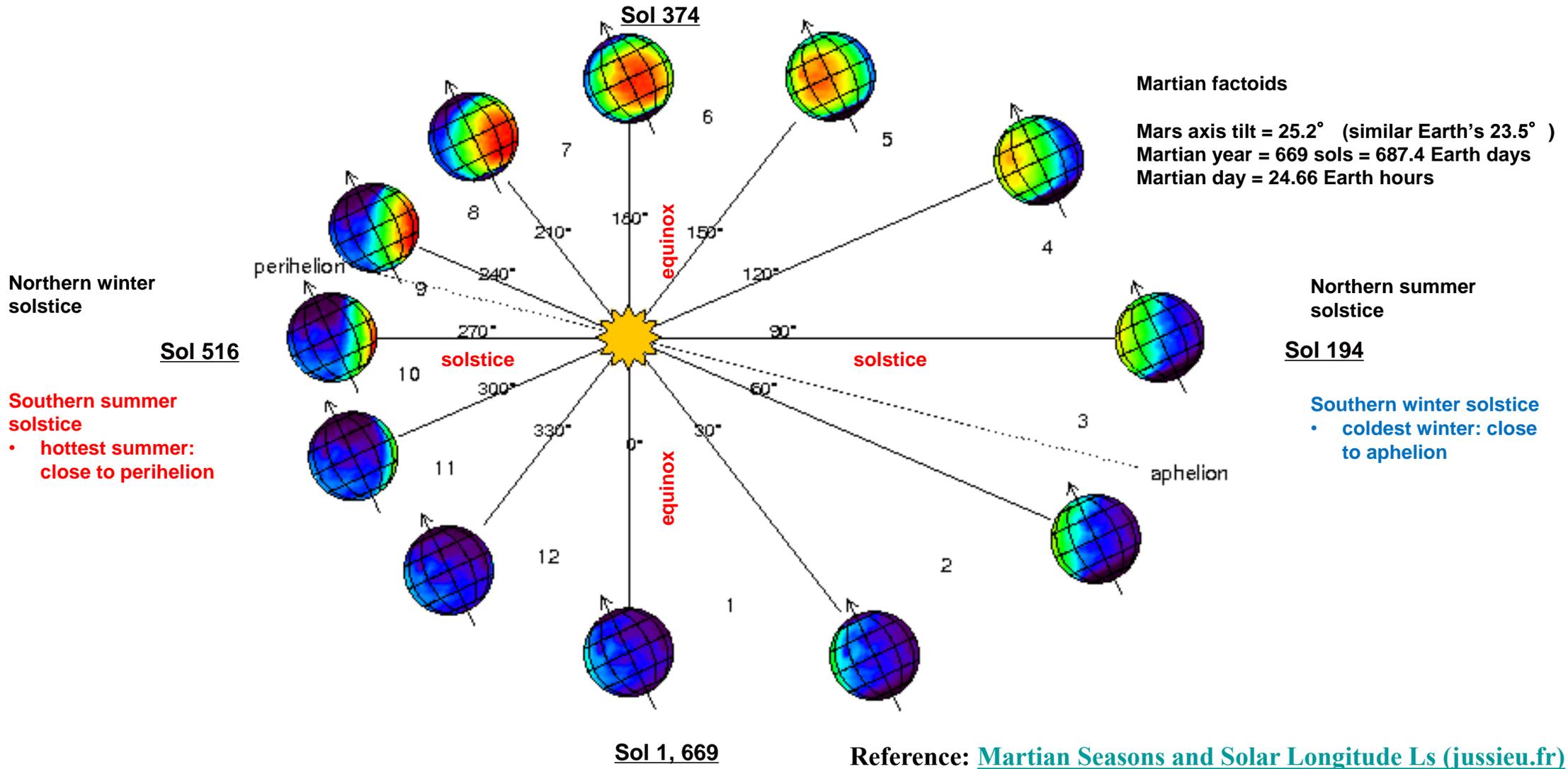
Thermal & Fluids Analysis Workshop
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Overview

- **Purpose: establish thermal boundary conditions from Martian climate data**

- **Parameters driving thermal environment for this study:**
  - **Latitude:**
    - **-50, -25, 0, +25, and +50 degrees**
    - **Going closer to the poles results in much less solar array input and risks polar cap involvement**
  - **Optical depth (tau-factor or simply dustiness)**
    - **Tau = 0.02 (exceptionally clear), Tau = 1.0 (nominally dusty), and Tau = 5.0 (very dusty)**
    - **Tau as high as 10 has been observed but not considered since solar transmissivity already < 1% for Tau = 5, so considering even higher Tau factors judged unproductive**
  - **Hot or Cold condition (WCH = worst-case hot, WCC = worst-case cold)**
    - **Driven by ground surface albedo and thermal inertia as well as convection to surface level ambient temperature**
    - **Minimum thermal inertia results in both WCH and WCC conditions due to faster ground surface temperature response to diurnal solar radiation changes**
    - **High albedo corresponds WCC condition (less solar energy absorbed by the ground)**
    - **Low albedo results in WCH condition (more solar energy absorbed by the ground)**
    - **Convection coefficients**
      - **0.4 and 4.0 W/m^2-K for WCH and WCC conditions, respectively**
      - **Taken from guidelines developed for Mars Sample Return (MSR) work**

The Martian orbit and seasons

Sol 374

Martian factoids

Mars axis tilt = 25.2° (similar Earth's 23.5°)
Martian year = 669 sols = 687.4 Earth days
Martian day = 24.66 Earth hours

Northern winter solstice

Sol 516

Southern summer solstice
- **hottest summer: close to perihelion**

Northern summer solstice

Sol 194

Southern winter solstice
- **coldest winter: close to aphelion**

perihelion

aphelion

equinox

solstice

solstice

equinox

Sol 1, 669

Reference: Martian Seasons and Solar Longitude Ls (jussieu.fr)

Overview: the case matrices

Cold cases

Latitude	Tau = 0.02	Tau = 1.0	Tau 5.0
-50°	WCC 1	WCC 6	WCC 11
-25°	WCC 2	WCC 7	WCC 12
0°	WCC 3	WCC 8	WCC 13
25°	WCC 4	WCC 9	WCC 14
50°	WCC 5	WCC 10	WCC 15

Maximum albedo and minimum thermal inertia at each latitude

Hot cases

Latitude	Tau = 0.02	Tau = 1.0	Tau 5.0
-50°	WCH 1	WCH 6	WCH 11
-25°	WCH 2	WCH 7	WCH 12
0°	WCH 3	WCH 8	WCH 13
25°	WCH 4	WCH 9	WCH 14
50°	WCH 5	WCH 10	WCH 15

Minimum albedo and minimum thermal inertia at each latitude

# Thermal boundary conditions needed for analysis

- **Solar radiation**
  - **Directional solar flux (line of sight)**
  - **Diffuse solar flux (from entire sky)**
  - **Optical depth affects solar radiation**
    - **Diminishes total flux (both directional and diffuse components), but**
    - **Also increases diffuse component relative to directional component**

- **Temperature**
  - **Overhead temperatures**
    - **Effective infrared sky sink temperature**
    - **Surface level ambient temperature**
    - **Sky sink versus ambient temperature**
      - **For clear skies, the sky temperature tends to be colder than ambient temperature**
      - **For dustier skies, sky versus ground temperatures differ less**
  - **Ground surface temperature**

How to get the thermal boundary conditions

- **Select cases: define latitude, tau-factor, and surface albedo and thermal inertia for the desired cases: 30 cases**

- **JPL ran the "1D instantiation of the MarsWRF" (WRF = Weather Research and Forecasting) model**
  - **Vertical 1D model of one surface location**
  - **Specify latitude, albedo, and thermal inertia and assume it applies at all longitudes**
  - **1D means**
    - **Relatively fast solution times**
    - **Lacks lateral pressure gradient prediction, so cannot predict surface level winds – hence the choice to use convection guidelines developed for previous Martian surface thermal analysis**
  - **Produces 1 Martian year of simulated thermal environment data per case**
    - **Data generated in 160 intervals per sol (9 Martian minute intervals)**
    - **Includes everything needed to develop thermal boundary conditions**
    - **But does not identify the WCC or WCH sol for analysis – that requires further processing**

- **Fortran post processor developed**
  - **To sift through the Martian year and identify the WCC or WCH sol for each case**
  - **Write the output in Thermal Desktop friendly format (for direct copy/paste into tables)**

The process flow
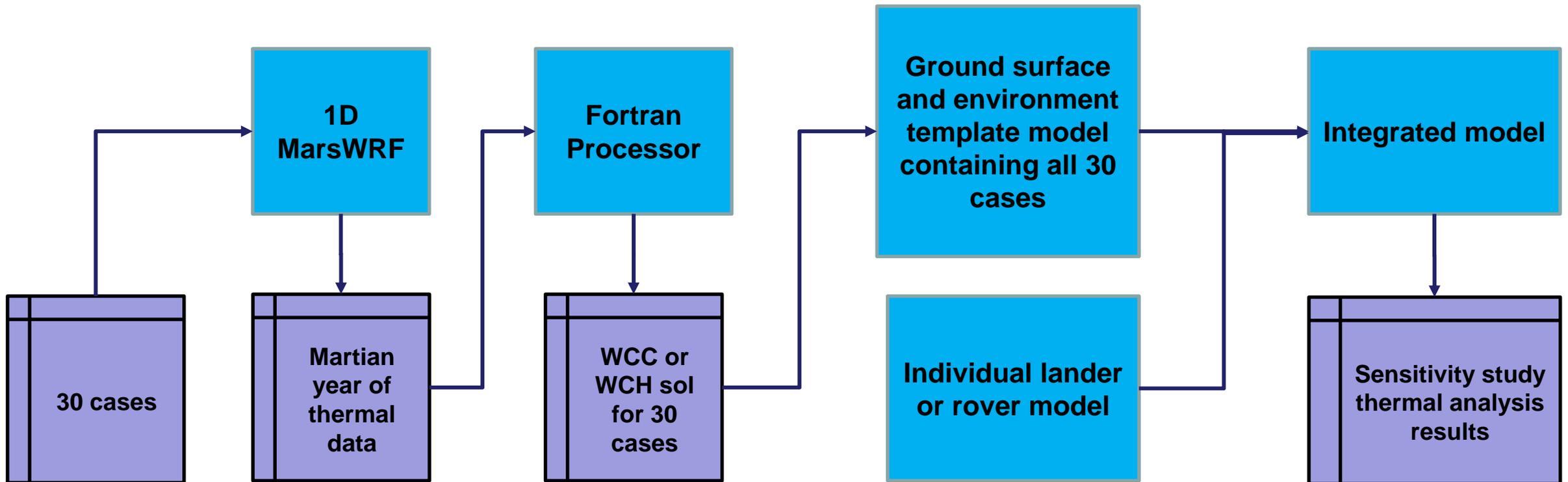
Mars ground albedo map

MCD_v6.1 with climatology average solar scenario. Ls 270.0deg.
Altitude 10.0 m ALS. Local time 0.0h (at longitude 0)

$0.105 \leq albedo \leq 0.315$

GCM surface bare ground albedo

Latitudes chosen for this study
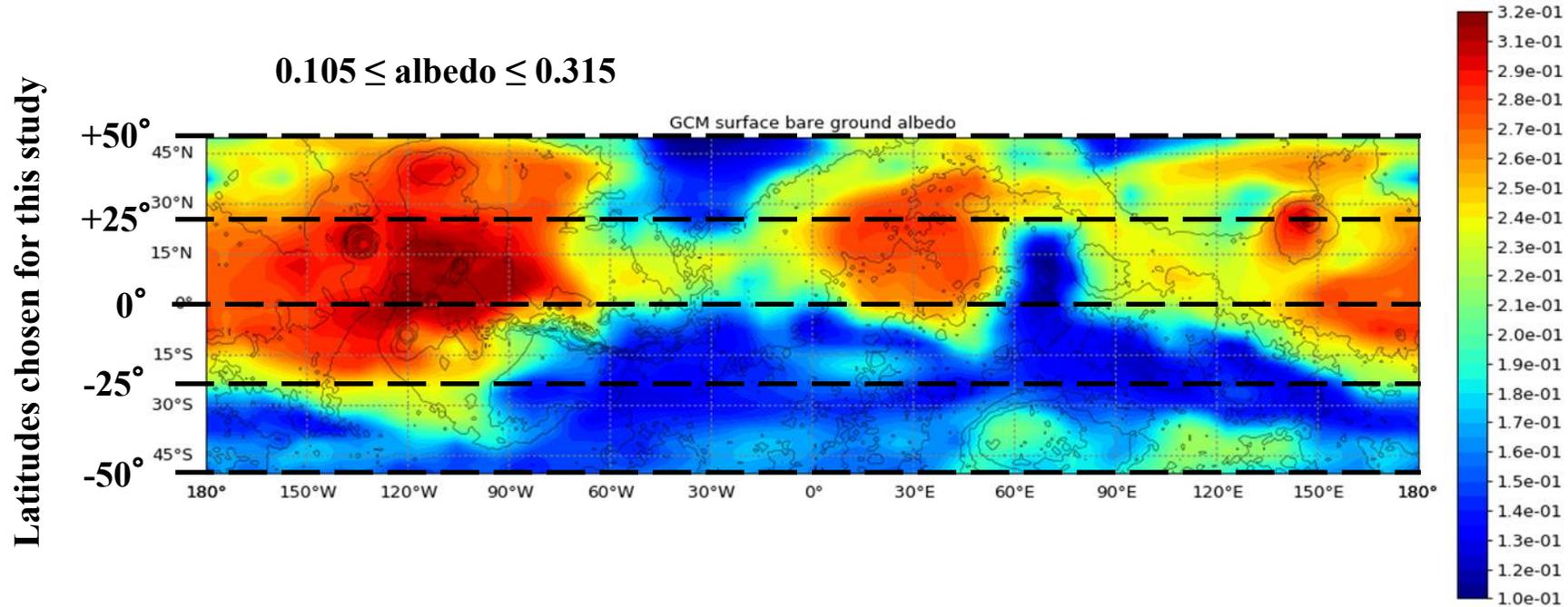
Mars Climate Database (c) LMD/OU/IAA/ESA/CNES

Reference: Mars Climate Database v6.1: The Web Interface (jussieu.fr)

Mars ground thermal inertia map

MCD_v6.1 with climatology average solar scenario. Ls 270.0deg.
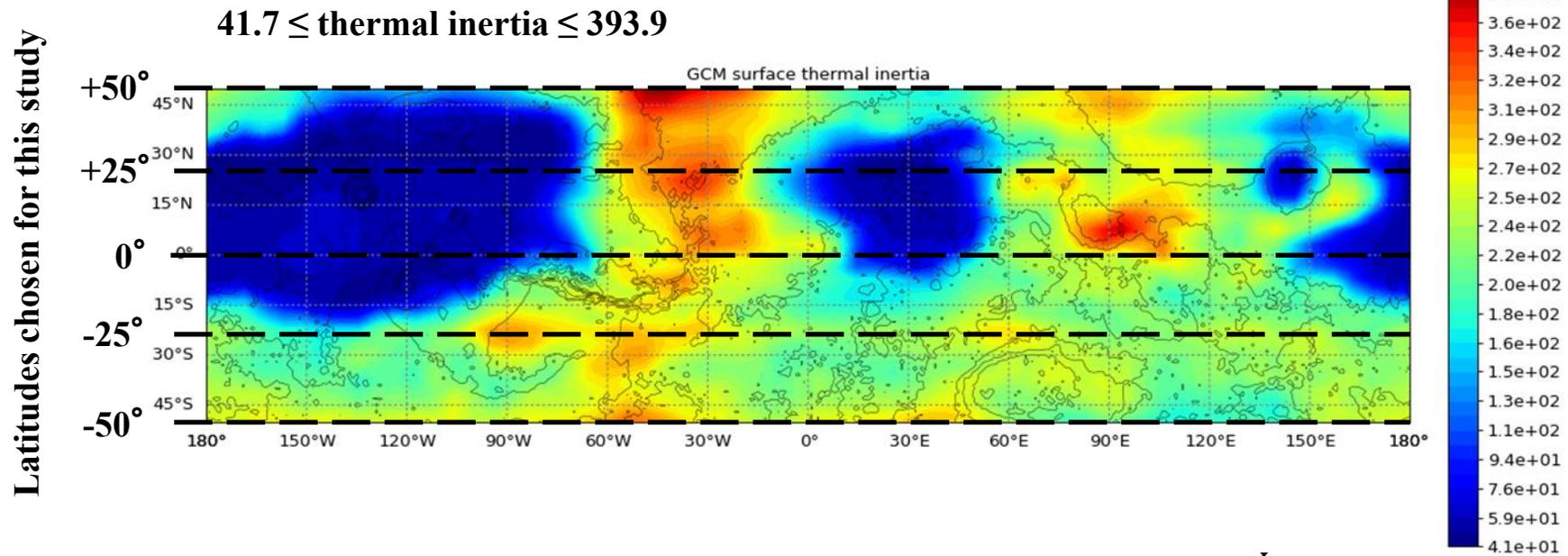Altitude 10.0 m ALS. Local time 0.0h (at longitude 0)

41.7 ≤ thermal inertia ≤ 393.9

GCM surface thermal inertia

Latitudes chosen for this study

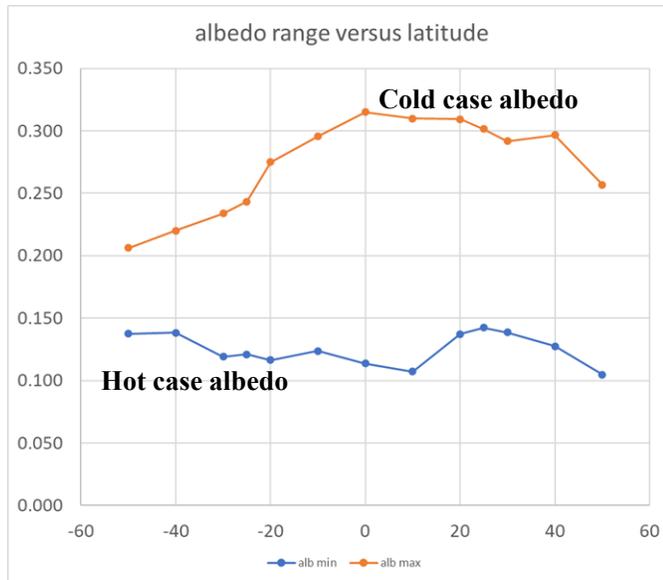Minimum surface thermal inertia drives worst case for both hot and cold extremes.

Low thermal inertia means surface temperature responds faster to diurnal solar heating variations resulting both hotter and colder temperature extremes

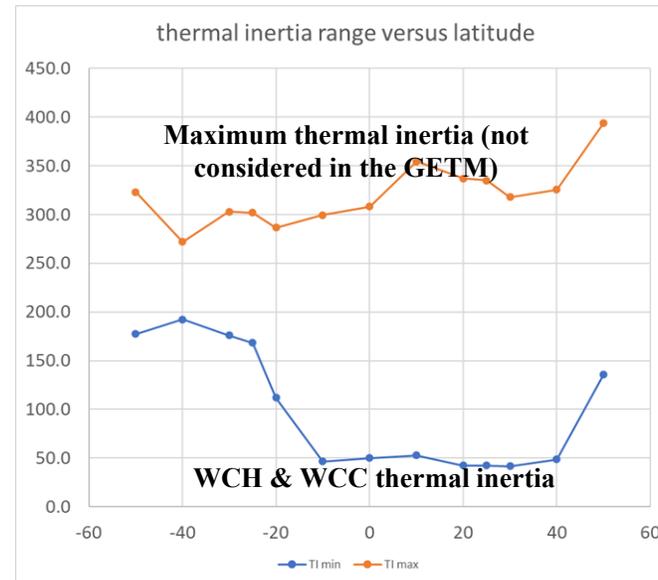$$Thermal\ Inertia = \sqrt{(Thermal\ Conductivity)(Density)(Specific\ Heat)}\ \left[\frac{J}{s^{0.5} \cdot m^2 \cdot K}\right]$$

Mars Climate Database (c) LMD/OU/IAA/ESA/CNES

Reference: Mars Climate Database v6.1: The Web Interface (jussieu.fr)

Max/min albedo vs latitude

albedo range versus latitude

Cold case albedo

Hot case albedo

Max/min thermal inertia vs latitude

thermal inertia range versus latitude

Maximum thermal inertia (not considered in the GETM)

WCH & WCC thermal inertia

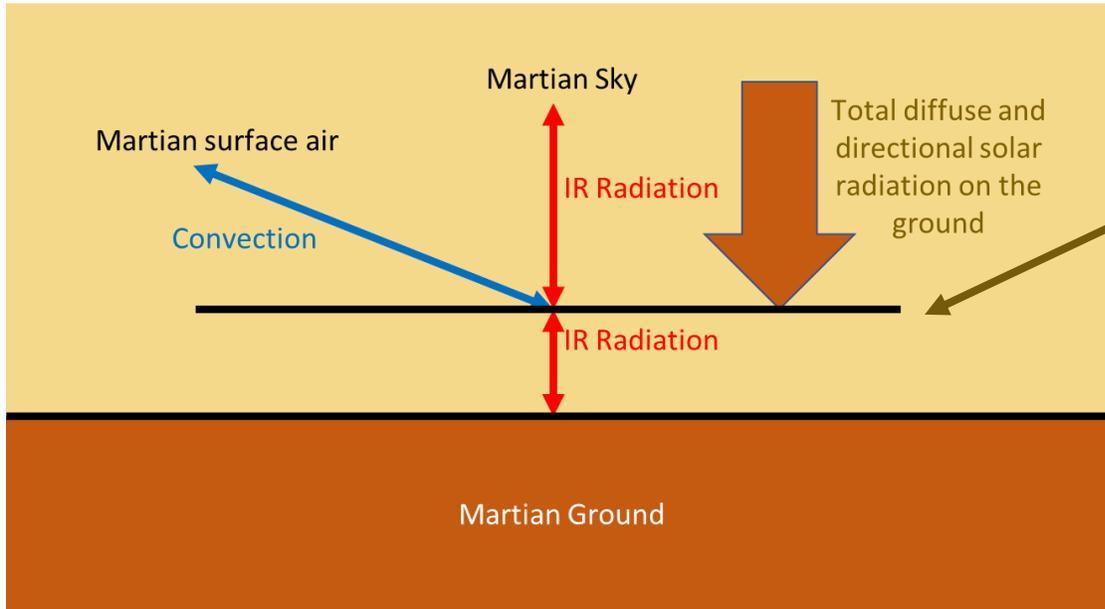| latitude	alb min	alb max	TI min	TI max
-50	0.137	0.206	177.2	323.2
-40	0.138	0.220	192.2	271.8
-30	0.119	0.234	175.8	302.9
-25	0.121	0.243	168.3	302.0
-20	0.117	0.275	111.9	286.4
-10	0.124	0.295	46.6	299.6
0	0.114	0.315	50.0	308.2
10	0.107	0.310	52.6	354.5
20	0.137	0.309	42.4	337.0
25	0.142	0.302	42.1	335.0
30	0.139	0.292	41.7	317.8
40	0.128	0.297	48.7	325.4
50	0.105	0.257	135.8	393.9

Highlighted cases used in this study

Reference: Mars Climate Database v6.1: The Web Interface (jussieu.fr)

Martian days, hours, minutes – require conversion to standard seconds for Thermal Desktop

sol	hr	min	T_{surf}	T_{air}	T_{sky}	Cos(Zenith)	q_{direct}	$q_{diffuse}$	L_s
432	9	36	279.952	241.338	164.435	0.760725	262.996	145.521	215.642960
432	9	45	283.072	243.009	165.684	0.783704	276.413	148.347	215.646912
432	9	54	286.004	244.582	166.921	0.805472	289.221	150.990	215.650848
432	10	3	288.697	246.456	168.153	0.825994	301.376	153.452	215.654785
432	10	12	291.226	248.905	169.360	0.845241	312.843	155.737	215.658707
432	10	21	293.570	251.211	170.553	0.863097	323.537	157.837	215.662643
432	10	30	295.775	253.447	171.745	0.879710	333.531	159.775	215.666580
432	10	39	297.779	255.561	172.915	0.894964	342.745	161.540	215.670532
432	10	48	299.603	257.536	174.044	0.908835	351.152	163.134	215.674469
432	10	57	301.254	259.389	175.133	0.921302	358.730	164.559	215.678391
432	11	6	302.736	261.132	176.188	0.932295	365.429	165.809	215.682327
432	11	15	304.061	262.759	177.205	0.941904	371.298	166.896	215.686264
432	11	24	305.225	264.279	178.180	0.950059	376.287	167.815	215.690201
432	11	33	306.231	265.725	179.116	0.956745	380.383	168.566	215.694138
432	11	42	307.087	267.112	180.024	0.961954	383.576	169.149	215.698059
432	11	51	307.800	268.433	180.912	0.965661	385.850	169.562	215.702011
432	12	0	308.373	269.675	181.780	0.967899	387.221	169.810	215.705948
432	12	9	308.805	270.831	182.616	0.968641	387.673	169.891	215.709885
432	12	18	309.095	271.900	183.417	0.967887	387.205	169.805	215.713821
432	12	27	309.245	272.867	184.179	0.965637	385.818	169.551	215.717743
432	12	36	309.253	273.747	184.900	0.961918	383.528	169.131	215.721680
432	12	45	309.121	274.545	185.586	0.956697	380.319	168.543	215.725632
432	12	54	308.847	275.263	186.235	0.949999	376.208	167.787	215.729568
432	13	3	308.433	275.901	186.849	0.941833	371.206	166.863	215.733505
432	13	12	307.879	276.461	187.427	0.932212	365.323	165.770	215.737427
432	13	21	307.188	276.943	187.968	0.921209	358.611	164.516	215.741364
432	13	30	306.354	277.345	188.474	0.908732	351.021	163.087	215.745316

- **Input to the MarsWRF Fortran post processor**

- **Data is from the WCH condition for latitude = 0° and Tau = 1.0**

- **Direct solar flux in this table is normal to the ground**

- **To get directional solar flux (along the line of sight to the sun) needed for the thermal model, divide by cos(zenith angle)**

- **The highlighted line is 432nd sol at local noon**

Determining the worst-case sol

Martian Sky

Martian surface air

Convection

IR Radiation

Total diffuse and directional solar radiation on the ground

IR Radiation

Martian Ground

Sensor plate ($\alpha = 0.3$ and $\varepsilon = 1.0$) in thermal equilibrium with the environment

Convection:
h = 0.4 W/m²-K for WCH
h = 4.0 W/m²-K for WCC

JPL recommended these convection coefficients as thermal environments for MSR analysis

Calculate the equilibrium temperature of this plate with this environment and use results as the metric for judging which sol is WCH or WCC

Energy balance with environment

$$Q_i + \alpha \cdot A \cdot F_s \cdot q_{stot} = \sigma \cdot \varepsilon \cdot F_s \cdot A \cdot \left(T^4 - T_s{}^4\right) + \sigma \cdot \varepsilon \cdot F_g \cdot A \cdot \left(T^4 - T_g{}^4\right) + h \cdot A \left(T - T_a\right)$$

Rearrange for 4th order polynomial which is solved in the MarsWRF Fortran post processor using Newton's Method

$$0 = T^4 + \frac{h}{\sigma \cdot \varepsilon} \cdot T - \left(\frac{Q_i}{\sigma \cdot \varepsilon \cdot A} + \frac{\alpha \cdot F_s \cdot q_{stot}}{\sigma \cdot \varepsilon} + \left(F_s \cdot T_s{}^4 + F_g \cdot T_g{}^4\right) + \frac{h \cdot T_a}{\sigma \cdot \varepsilon} \right)$$

```
*****************************************************************
*
* Result for case name: 1D_WCH_lat0_tau1
*  Environment parameter extremes on each sol
*
*****************************************************************
* WCH day based on
* max instantaneous sensor plate temperature (h = 0.4 W/m2-K)
*****************************************************************
```

Worst-case hot
Latitude = 0°
Tau = 1.0
WCH sol = 429

time (sec)	T_air (K): sol=429		time (sec)	T_srf (K): sol=429		time (sec)	_sky (K): sol=429		time (sec)	Q_dif (W/m²): sol=429		time (sec)	Q_dir (W/m2): sol=429
0	182.249		0	175.715		0	161.752		0	0		0	0
554.845	181.847		554.845	175.35		554.845	161.424		554.845	0		554.845	0
1109.69	181.452		1109.69	174.99		1109.69	161.099		1109.69	0		1109.69	0
1664.535	181.063		1664.535	174.637		1664.535	160.777		1664.535	0		1664.535	0
2219.38	180.681		2219.38	174.29		2219.38	160.459		2219.38	0		2219.38	0
2774.225	180.305		2774.225	173.948		2774.225	160.145		2774.225	0		2774.225	0
3329.07	179.936		3329.07	173.612		3329.07	159.834		3329.07	0		3329.07	0
⋮			⋮			⋮			⋮			⋮	
39393.995	255.562		39393.995	297.794		39393.995	172.901		39393.995	161.279		39393.995	382.285
39948.84	257.536		39948.84	299.617		39948.84	174.029		39948.84	162.871		39948.84	385.674
40503.685	259.387		40503.685	301.268		40503.685	175.118		40503.685	164.293		40503.685	388.657
41058.53	261.129		41058.53	302.75		41058.53	176.173		41058.53	165.541		41058.53	391.24
41613.375	262.755		41613.375	304.074		41613.375	177.189		41613.375	166.626		41613.375	393.461
42168.22	264.275		42168.22	305.238		42168.22	178.164		42168.22	167.544		42168.22	395.319
42723.065	265.721		42723.065	306.243		42723.065	179.099		42723.065	168.293		42723.065	396.824
43277.91	267.108		43277.91	307.099		43277.91	180.007		43277.91	168.875		43277.91	397.986
43832.755	268.429		43832.755	307.811		43832.755	180.896		43832.755	169.288		43832.755	398.806
44387.6	269.671		44387.6	308.385		44387.6	181.763		44387.6	169.536		44387.6	399.297
44942.445	270.826		44942.445	308.816		44942.445	182.6		44942.445	169.617		44942.445	399.457
45497.29	271.893		45497.29	309.107		45497.29	183.4		45497.29	169.531		45497.29	399.286
46052.135	272.859		46052.135	309.256		46052.135	184.161		46052.135	169.277		46052.135	398.784
46606.98	273.738		46606.98	309.265		46606.98	184.881		46606.98	168.859		46606.98	397.953
47161.825	274.536		47161.825	309.132		47161.825	185.567		47161.825	168.271		47161.825	396.78
47716.67	275.253		47716.67	308.858		47716.67	186.216		47716.67	167.516		47716.67	395.263

midnight

noon

Each shaded region contains one of the time dependent thermal boundary conditions needed for thermal analysis – in copy-paste ready form for Thermal Desktop

Thermal model ready boundary conditions
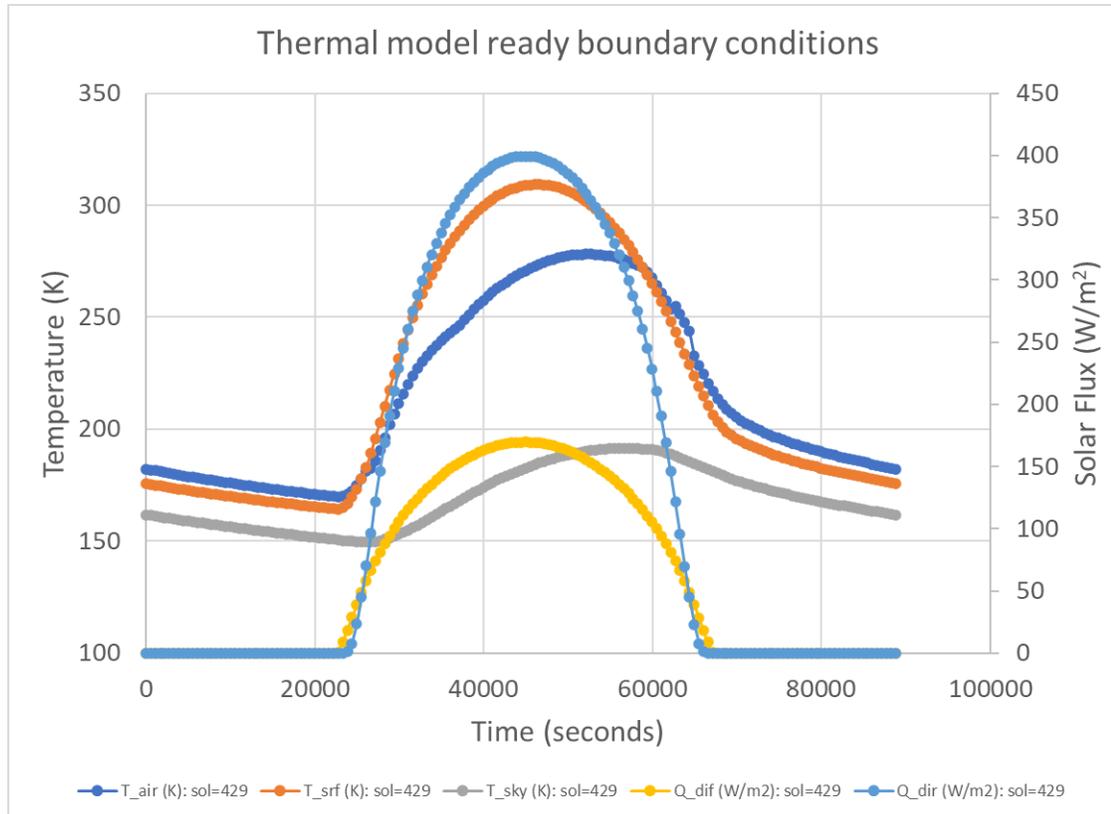
- **These curves are loaded into the ground/environment template model 30 times**
  - **15 times each WCC-latitude-tau combination**
  - **15 times each WCH-latitude-tau combination**

- **Direct solar flux corresponds to the solar line of sight vector direction**

Case matrices for analysis sensitivity study

Cases with WCH and WCC sols selected

Cold cases			
Latitude	Tau = 0.02	Tau = 1.0	Tau 5.0
-50°	Thermal inertia = 177.2, Albedo = 0.206, sol 239	Thermal inertia = 177.2, Albedo = 0.206, sol 250	Thermal inertia = 177.2, Albedo = 0.206, sol 264
-25°	Thermal inertia = 168.3, Albedo = 0.243, sol 193	Thermal inertia = 168.3, Albedo = 0.243, sol 194	Thermal inertia = 168.3, Albedo = 0.243, sol 195
0°	Thermal inertia = 50.0, Albedo = 0.315, sol 177	Thermal inertia = 50.0, Albedo = 0.315, sol 179	Thermal inertia = 50.0, Albedo = 0.315, sol 180
25°	Thermal inertia = 42.1, Albedo = 0.302, sol 527	Thermal inertia = 42.1, Albedo = 0.302, sol 526	Thermal inertia = 42.1, Albedo = 0.302, sol 524
50°	Thermal inertia = 135.8, Albedo = 0.257, sol 541	Thermal inertia = 135.8, Albedo = 0.257, sol 557	Thermal inertia = 135.8, Albedo = 0.257, sol 572

Hot cases			
Latitude	Tau = 0.02	Tau = 1.0	Tau 5.0
-50°	Thermal inertia = 177.2, Albedo = 0.136, sol 507	Thermal inertia = 177.2, Albedo = 0.136, sol 509	Thermal inertia = 177.2, Albedo = 0.136, sol 511
-25°	Thermal inertia = 168.3, Albedo = 0.121, sol 495	Thermal inertia = 168.3, Albedo = 0.121, sol 496	Thermal inertia = 168.3, Albedo = 0.121, sol 499
0°	Thermal inertia = 50.0, Albedo = 0.114, sol 436	Thermal inertia = 50.0, Albedo = 0.114, sol 429	Thermal inertia = 50.0, Albedo = 0.114, sol 420
25°	Thermal inertia = 42.1, Albedo = 0.142, sol 354	Thermal inertia = 42.1, Albedo = 0.142, sol 343	Thermal inertia = 42.1, Albedo = 0.142, sol 320
50°	Thermal inertia = 135.8, Albedo = 0.105, sol 248	Thermal inertia = 135.8, Albedo = 0.105, sol 235	Thermal inertia = 135.8, Albedo = 0.105, sol 220

Environment parameter insights

- **Optical depth – a high tau factor**
  - **Both blocks and scatters solar radiation**
  - **Increases diffuse scattered solar radiation relative to clear conditions**
  - **Decreases total (direct + diffuse) solar radiation**
  - **Increases the sky infrared sink temperature**

- **Albedo**
  - **High albedo corresponds to a colder ground temperature but increases reflected solar heating on a rover or lander**
  - **Low albedo corresponds to a warmer ground temperature but decreases reflected solar heating on a rover or lander**

- **Thermal inertia ($= \sqrt{k_{ground}\rho_{ground}C_{p,ground}} \ [J/m^2/sec^{0.5}/K]$)**
  - **Low TI corresponds to larger hot/cold temperature excursions in response to diurnal solar radiation**
  - **High TI corresponds to smaller hot/cold temperature excursions in response to diurnal solar radiation**
  - **Therefore, low TI is chosen for both worst case hot and cold consideration**

latitude	tau	hot or cold	albedo	Tmax	sol_Tmax
-50	0.02	hot	0.137	283	507
-25	0.02	hot	0.121	289.7	495
0	0.02	hot	0.114	289	436
25	0.02	hot	0.142	276.4	354
50	0.02	hot	0.105	261.8	248
-50	1	hot	0.137	279	509
-25	1	hot	0.121	286.2	496
0	1	hot	0.114	284.4	429
25	1	hot	0.142	271.9	343
50	1	hot	0.105	256.8	235
-50	5	hot	0.137	260.5	511
-25	5	hot	0.121	266.5	500
0	5	hot	0.114	258.5	421
25	5	hot	0.142	246.6	316
50	5	hot	0.105	234.3	218

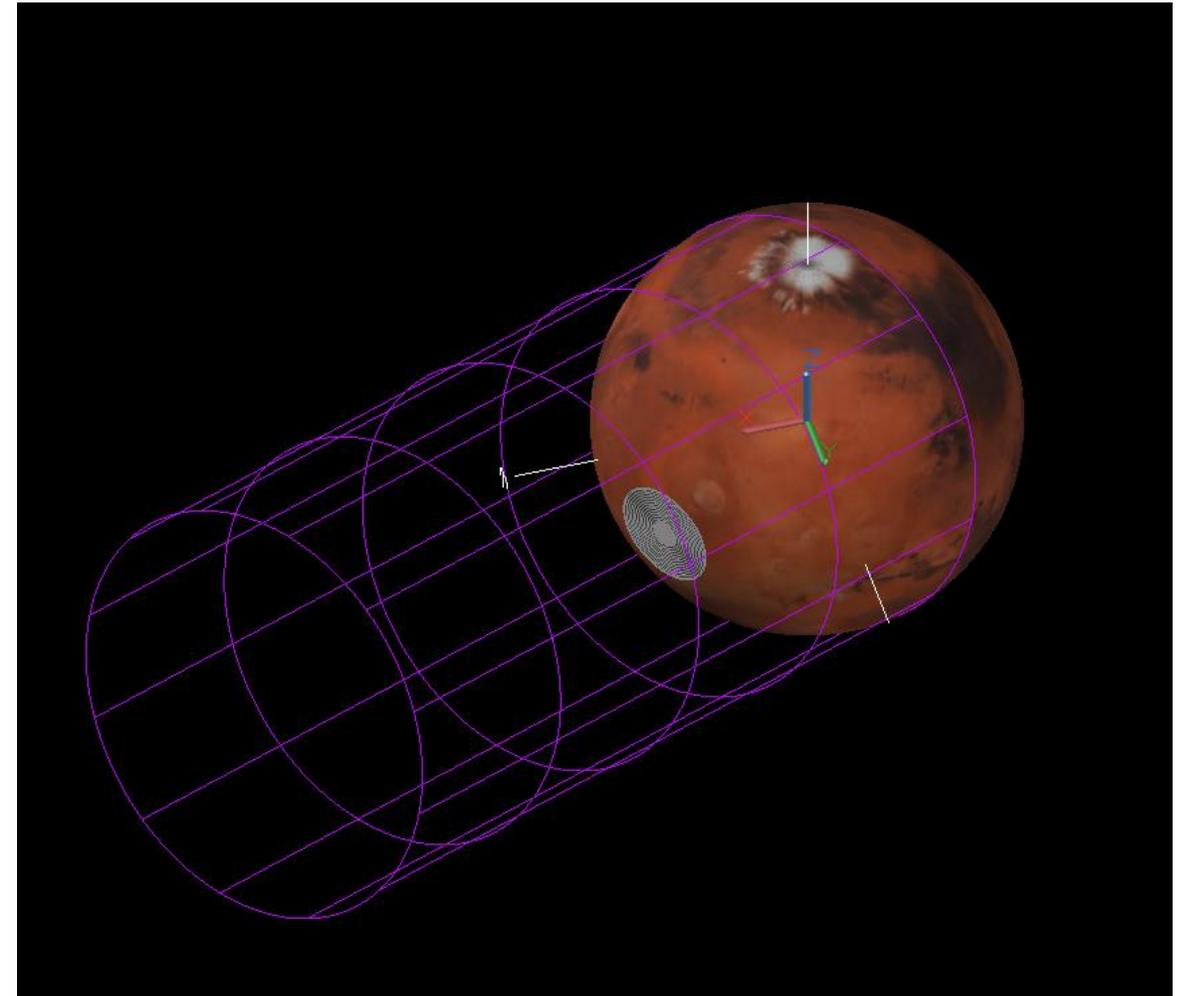| latitude	tau	hot or cold	albedo	Tmin	sol_Tmin
-50	0.02	cold	0.206	132.8	238
-25	0.02	cold	0.243	142.5	193
0	0.02	cold	0.315	142.3	176
25	0.02	cold	0.302	142.4	527
50	0.02	cold	0.257	137.6	540
-50	1	cold	0.206	129.5	249
-25	1	cold	0.243	146.4	193
0	1	cold	0.315	148.1	179
25	1	cold	0.302	145.7	526
50	1	cold	0.257	137.5	553
-50	5	cold	0.206	130.2	263
-25	5	cold	0.243	153.8	194
0	5	cold	0.315	168.5	181
25	5	cold	0.302	160.2	525
50	5	cold	0.257	139	561

Consistent with orbit-derived intuition:
- **Hottest day always occurs at -25° latitude regardless of optical depth**
- **Coldest day always occurs at -50° latitude regardless of optical depth**

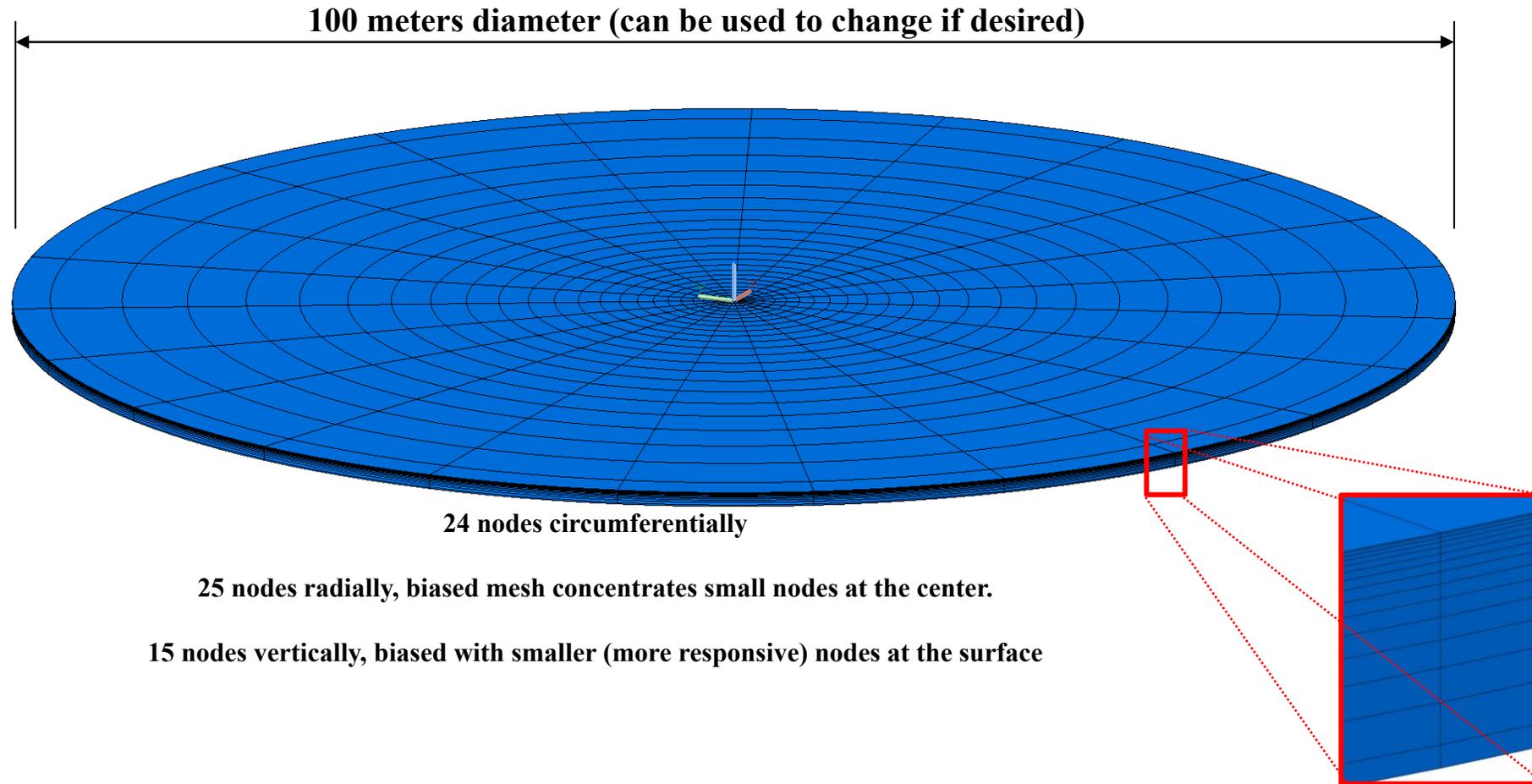**Hottest hot day is sol 495 with tau = 0.02 at -25° latitude**

Coldest cold day is sol 249 with tau = 1.0 at -50° latitude

Atmospheric dust affects which sol is hottest or coldest

- **Models the Martian ground surface to a depth of 1 meter**
  - Vertical 15 node biased mesh with thin surface node and progressively thicker nodes with increasing depth

- **All 30 cases preloaded and preprogrammed in the model**

- **2 user selectable ground modeling options**
  - Entire ground can be treated as a boundary condition using temperature predictions from 1D MarsWRF
  - To include shadowing effects in IR ground coupling, can calculate the ground temperature

- **2 user selectable simulation options**
  - Stepwise steady state – computes steady state temperature at each time slide through the sol
  - Transient – computes transient temperature response, repeating the diurnal cycle until the solution repeats and becomes periodic

- **Simulation time starts at midnight**

- **Ground modeling has been validated and shown to closely approximate the surface temperature predictions from MarsWRF**

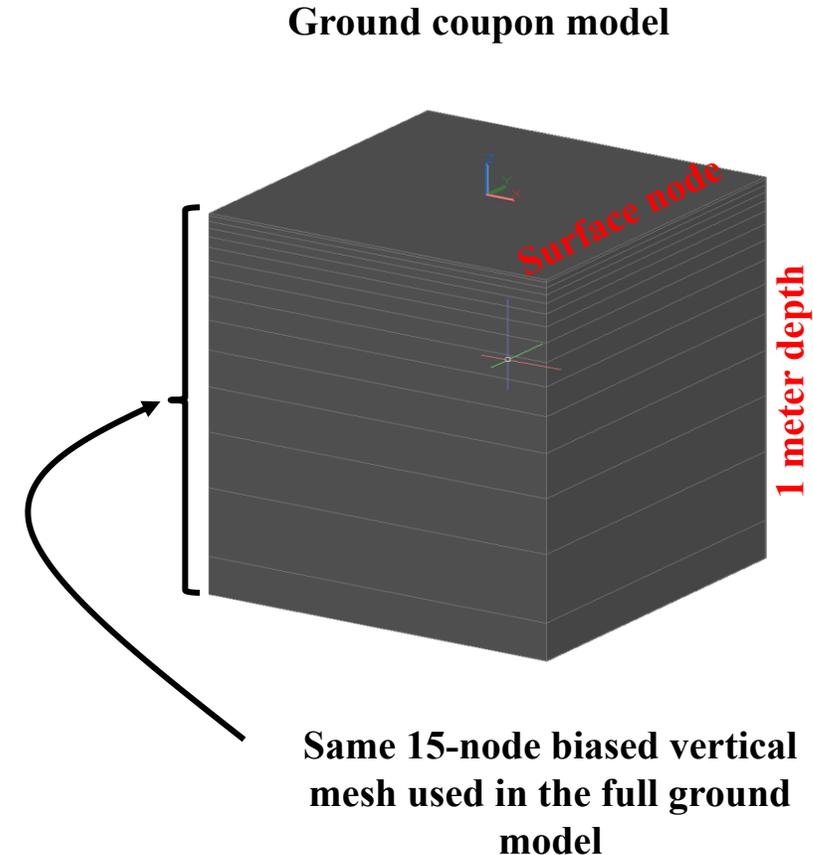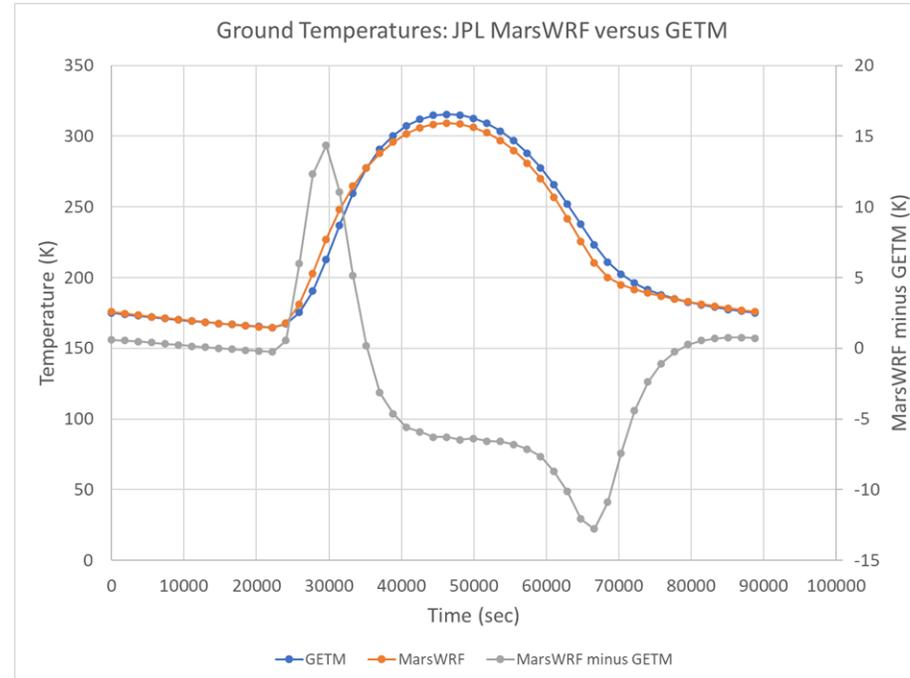**Orbit view showing the ground disk at 0° latitude at local midnight**

The ground disk

100 meters diameter (can be used to change if desired)

24 nodes circumferentially

25 nodes radially, biased mesh concentrates small nodes at the center.

15 nodes vertically, biased with smaller (more responsive) nodes at the surface
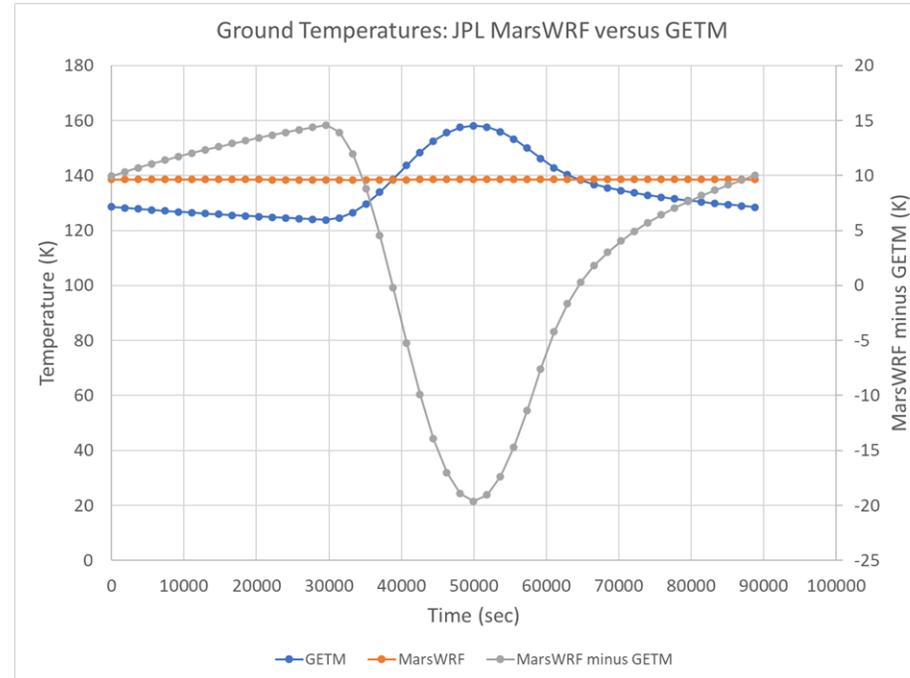
1 meter thick

- User guide developed and provided to analyst team members aids using the ground model for trade studies

- All 30 environments preprogrammed and user-selectable

- Simulation modes
  - Piecewise steady state – runs steady state simulation at 1 Martian hour increments
  - Cyclic transient – time-dependent transient simulation that repeats until reaching quasi steady state

- Ground simulation modes
  - Boundary mode
    - Controls the ground temperature to match MarsWRF predictions
    - Used for piecewise steady state mode
    - This mode cannot capture shadowing effects in IR heat transfer between lander/rover and the ground
  - Simulation mode
    - Calculates the ground temperature during simulation
    - Used for cyclic transient mode
    - This mode captures shadowing effects in IR heat transfer between lander/rover and the ground

- **Validation criterion – the ground model comes close to duplicating the ground surface temperatures predicted by the JPL MarsWRF climate simulator**
    - Exception – larger variances are seen for cases when MarsWRF predicts the ground to be frosted with solid CO_2
    - This occurs closer to the poles between 137K and 148K, depending on ground elevation (i.e., ambient pressure)
    - The ground model does not include CO_2 sublimation/accretion

- **All 30 environments and all 60 case sets were defined in a small "ground coupon" model**
    - 1 m by 1 m patch of ground modeled to a depth of 1 m with the same 15 node biased vertical meshed used in the full model
    - Why?
        - Allowed faster solutions
    - Allowed easier debugging of heating rates since heat and heat flux are numerically identical for unit-area surface

- **Once all environments were defined and QC-checked, the environments, orbits, case sets, and logic objects were exported and then imported to the full ground model.**

Ground coupon model

1 meter depth

Surface node

Same 15-node biased vertical mesh used in the full ground model

Ground Temperatures: JPL MarsWRF versus GETM

Worst case hot, latitude = 0° , tau = 1.0

Ground Temperatures: JPL MarsWRF versus GETM

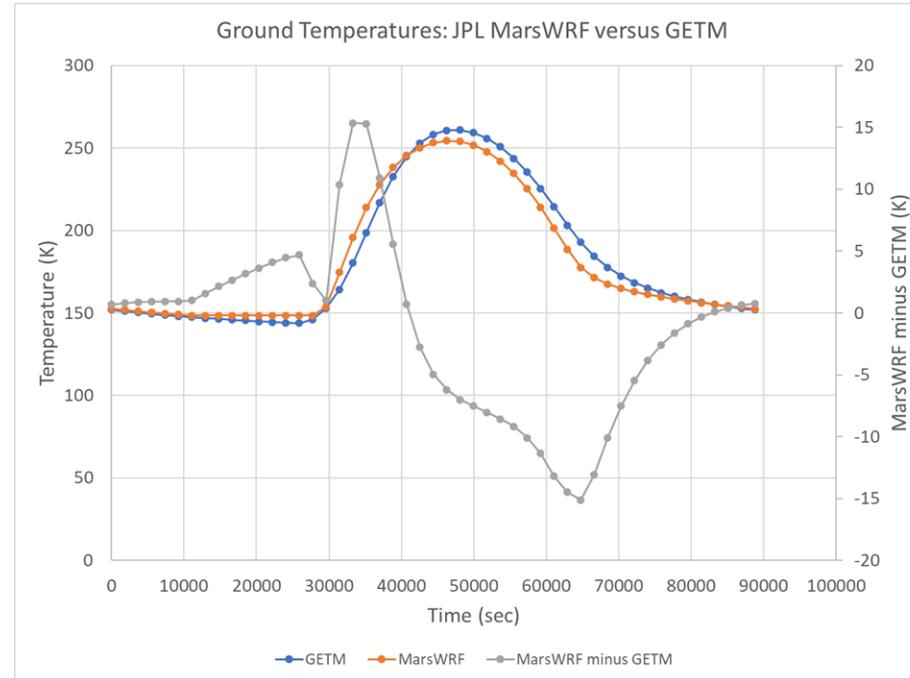**Worst case cold, latitude = -50°, tau = 1.0**

MarsWRF predicts constant ground temperature due to frozen CO$_2$ accretion

Using ground boundary mode handles this case since isothermal ground eliminates shadowing effect in IR thermal exchange with the ground

This condition occurs in 6 of the 15 cold cases

Ground Temperatures: JPL MarsWRF versus GETM


Legend: GETM — MarsWRF — MarsWRF minus GETM

Worst case cold, latitude = +25°, tau = 1.0

MarsWRF predicts constant nighttime ground temperature due to frozen CO$_2$ accretion but thaws during the day

Using ground simulation mode handles this case since ground surface temperature variations driven by nighttime CO$_2$ frost accretion are fairly minor

This condition occurs in 2 of the 15 cold cases

Ground temperatures: model versus MarsWRF

- The ground model proves to be usefully accurate, though variances are seen

- Variance sources include
  - MarsWRF has a more complete climate simulation tool includes thermophysical phenomena that are not practical to include in this ground model
  - By far, CO_2 sublimation/accretion is the most significant of these thermophysical phenomena
  - Contributors to minor variations likely include
    - Different ground temperature modeling effects
    - Slightly different ground thermal properties

Conclusions
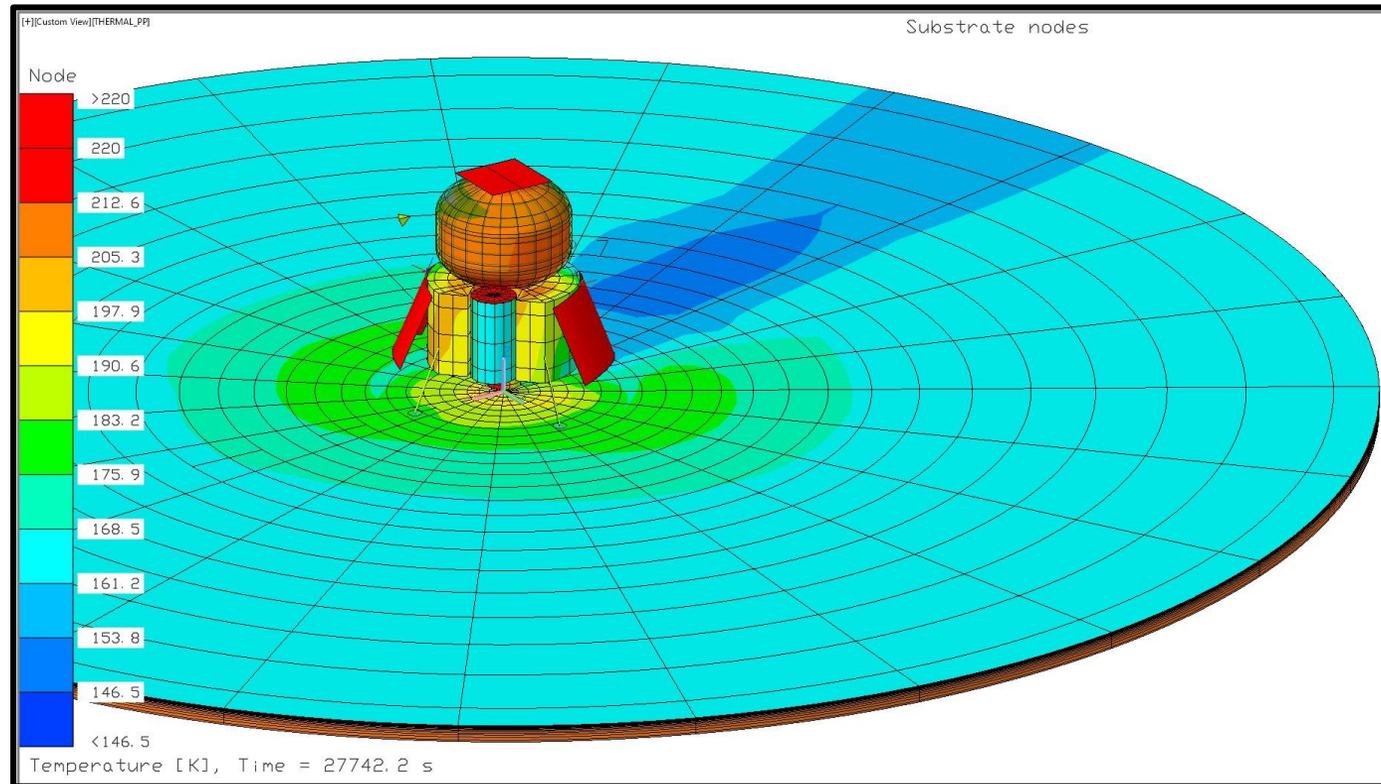
- **The GETM can be used as a starting template for Martian landers, vehicles, rovers, etc.**

- **This GETM provides 15 worst cases hot and 15 worst case cold Martian days for several latitudes and optical depths**
  - **Limitation: does not properly account for CO_2 ground frost, though work arounds exist**

- **Established process for adding more environments**

- **User guide was developed documenting usage**

Acknowledgements

- **Mars Climate Data Base**
  - **Ground albedo and thermal inertia:** **Mars Climate Database v6.1: The Web Interface (jussieu.fr)**
  - **Orbit and solar longitude image:** **Martian Seasons and Solar Longitude Ls (jussieu.fr)**
  - **Forget et al. 1999:** **Improved general circulation models of the Martian atmosphere from the surface to above 80 km - NASA/ADS (harvard.edu)**
  - **Millour et al. 2018:** **Abstract for Scientific Workshop "From Mars Express to ExoMars" (esa.int)**

- **Michael Mischna/JPL**
  - **Generating one-dimensional MarsWRF solutions providing Martian surface thermal environment data for various latitude, albedo, thermal inertia, and optical depth conditions**

Questions?